

# UNPUBLISHED PRELIMINARY DATA.

An Analog Study of System Protection

Ns 6-152-61

N 63 21072

Code 1

(NASA Grant NsG-152-61)

Duke Univ Durham, N.C.

## INTRODUCTION

T. G. Wilson [1962] 24 p 7 figs

(NASA CR-50940)

OTS: \$2.60 pk, \$0.92 mf

24p  
[2] synth  
The purpose of this appendage is to discuss an effort to facilitate the study of protection of scientific satellite power systems by providing an analog computer simulation of a typical system. Such a simulation would provide many opportunities for studying system protection problems. System operation could be slowed down by time scaling techniques, all system parameters could be readily varied, and faults inserted into the system. There are also many disadvantages to using a computer simulation of a system as a means of studying system protection. A given computer simulation is a model of the system only over a limited range. If the equations describing the system change form due to parameter changes or other stresses, the simulation must be changed also to remain valid. Also, approximations are usually involved when a system is described mathematically and these become inaccuracies in the simulation.

There are other limitations to a computer simulation study that should be pointed out. Satellite power systems are characteristically very non-linear and, consequently, difficult to simulate. Realistically, only circuit considerations should be included in the study since the inclusion of other stresses such as environment would greatly increase the complexity of the simulation. There are also limitations associated with faults that could be inserted in the simulation. A short circuit in the simulation, for example, would require that the input and output impedances of the electrically near-by components be included in the simulation in order to see the effects of the short. This, too, would greatly increase the complexity of the simulation.

The effort described here is an initial step toward an analog simulation as a means of studying system protection. Many problems are pointed out and some successes noted. It is hoped that further work will result.

## OTS PRICE

XEROX

\$

2.60

MICROFILM

\$

0.92

## Some Considerations

It has been pointed out that the electrical power system of a satellite is extremely nonlinear and, therefore, difficult to simulate. Frequently, the simulation of nonlinear systems can be simplified by including actual hardware components in the simulation. In a typical satellite electrical power system, for example, several courses of action are possible. In order to illustrate this, consider the simplified block diagram of a satellite electrical power system shown in Figure 1. A simulation of the Prime Converter-Regulator, for example, can be avoided by providing a substitute input to all points in the computer that the output of the Prime Converter-Regulator would go. This substitute input could be the output of an actual hardware Prime Converter-Regulator under certain conditions. A

similar situation would be to use an actual hardware converter to replace, for example, Converter "A". Here again, several conditions are imposed. First, the hardware element must be compatible with any time scaling or amplitude scaling required by the computer portion of the simulation. A simple first order filter, for example, could not be placed in a computer simulation that had been time scaled without having its corner frequency adjusted correspondingly. In some instances, circuits involving magnetic cores for example, time scale adjustments are not so easily made. A second problem with including hardware components in a computer simulation is the requirement that the hardware component have a high input impedance. In an analog computer, every variable is represented by a voltage at the output of an operational amplifier. Such amplifiers have high impedance outputs and, generally, cannot be used to drive hardware elements directly. Finally, it would generally be necessary to change a variable from its voltage analog back to its actual form before it could be used as an input to a hardware element. Likewise, computer inputs from hardware components must also be in voltage form. Switching transistors requiring low values of base current to saturate are good examples of hardware that could be realistically substituted in a simulation.

Because of the large number of magnetic-core devices in satellite electrical power supply systems, and because of the important, fundamental functions these devices perform, it is considered important that the characteristics of these devices be included as accurately as possible in the simulation of such systems. Simply substituting a square wave input for the output of a converter, for example, limits the simulation to the satellite's several experiments, and the inclusion in the simulation of actual magnetic-core devices introduces serious time and amplitude scaling and impedance matching problems. These reasons suggest that the magnetic core devices actually be simulated in the computer without hardware substitution. However, there are studies that could be made involving the protection of a single experiment within the satellite without attempting to simulate magnetic-core devices such as converters. The problems involved, and the solutions would be dependent upon each individual experiment. In the following discussions, attention is concentrated upon simulating magnetic-core devices.

### Obtaining the B-H Relationship

The simulation of circuits involving magnetic-core devices is made difficult by the extreme nonlinearity of the relationship between magnetic flux density (B) and magnetic field intensity (H). This is particularly true for "square-loop" magnetic materials. Combining such nonlinearities as backlash and saturation can result in a function with the characteristic shape of a major hysteresis loop, but these tend to become unstable as the hysteresis loop is made to become a square loop. A square loop can also be generated with bi-stable switching circuits, but requirements involving time are not readily satisfied in such circuits.

## An Analytic Expression.

An analytic expression relating B to H in the magnetic materials to be simulated, if not too complex, would be a most desirable aid in developing a simulation. It would provide a direct means of accomplishing the simulation; and, if the expression were a differential equation, it would likely provide the time derivative of B directly, eliminating a subsequent differential operation in the simulation. This would be a particular advantage since differentiation is avoided whenever possible in an analog computer and the time derivative of B will surely be required in the simulation.

Several efforts to obtain approximate analytical expressions relating B to H have been recorded. Some of these have used experimental methods to obtain expressions relating B and H in a given sample and for a limited set of conditions (1). Others have obtained expressions that described a given hysteresis loop (2). None of these expressions seem suitable for use in an analog computer simulation of magnetic-core characteristics. Generally the expressions are difficult to simulate, would require a prohibitive amount of equipment, and are useful only over a limited range of conditions. More recently, a theoretical expression has been derived that relates magnetic field intensity to the motion of a 180-degree domain wall in a magnetic material (3). This expression, also, is extremely nonlinear and would be difficult to apply to an analog computer.

The Van der Pol equation provided still another analytical approach to obtaining an expression relating B and H. The stimulus for this consideration was the similarity of the phase plane plot of the Van der Pol equation and the dB/dT versus H plot of many magnetic materials. Figure 2 shows a B-H loop obtained using the Van der Pol equation. The B-H loop illustrated in Figure 2 was generated in the following manner. The Van der Pol equation, Equation 1, was programmed for the analog computer. Figure 3 illustrates

$$\frac{d^2y}{dt^2} = k (1-y^2) \frac{dy}{dt} - y \quad (1)$$

the analog solution. The computer was operated until the problem settled into a limit cycle, and the period of the cycle was measured. It should be noted that any simulation utilizing this particular means of function generation would have to be time scaled to operate at a frequency corresponding to this period. Finally, a sinusoidal input was added as an input to the integrator computing  $+[20y]$ , as illustrated in Figure 4. This sinusoid was added after the problem was in a limit cycle and was caused to be zero and go positive as  $+[10y]$  became a positive value. If the added sinusoidal input  $e_a$  is H in Figure "4", then  $-[10\dot{y}]$  is B in Figure "4". It should be noted that the problem can be started with the limit cycle as an initial condition.

Figure 3 includes the details of this particular simulation. Considerable shaping of the B-H loop shown in Figure 2 can be accomplished by varying  $k$  in Equation 1 and the magnitude of the added sinusoidal input. No scale values are shown in Figure 2 since amplitude scaling in the computer can adjust the width and height of the loop to any desired value.

The complexities of this type of function generation are pointed out in the preceding paragraph. Several other disadvantages should be pointed out also. The function generation is only valid for a sinusoidal input of a fixed frequency. Also, since time is an independent variable in the Van der Pol equation, some complexity is added in time scaling the overall problem. However, this difficulty would not render the Van der Pol equation approach impractical in a problem requiring a fixed frequency sinusoidal excitation.

One particularly significant advantage of this function generator should also be pointed out. If the inputs to integrator number 22 are summed in an amplifier prior to integration,  $dB/dT$  would be available directly from the generator and a subsequent differentiation would be avoided.

Two additional analytic expressions should be recorded that have potential as a function generator relating  $B$  and  $H$ . Figure 5 shows a plot of Equation 2 for  $k_1 = 2$  and, as can be seen from the plot, it has the characteristic shape of a hysteresis loop.

$$B = \tanh (B + H \pm k_1) \quad (2)$$

Because of a lack of multiplying equipment, Equation 2 has not been simulated in the analog computer. However, the following observations should be recorded. The equation is time-independent and, consequently, would present no time scaling problems. The switching operation required by the double sign in the argument of the hyperbolic tangent occurs when  $B$  is a maximum value and should introduce no problems in the simulation. In order to program this equation, the hyperbolic tangent has to be represented by its equivalent, infinite series. Since only a limited number of terms can be used in the simulation, some accuracy is sacrificed. Finally, operation on minor loops may cause some difficulties in the switching operation. Figure 6 is an analog solution to Equation 2.

#### An Artificial Approach

An earlier report on this effort (4) discussed the work of Ohteru and Takehashi who developed and used successfully a function generator to simulate magnetic hysteresis characteristics (5,6,7). This generator was used in the simulation of a saturable reactor circuit and two magnetic amplifier circuits, and contributed significantly to a study of some specific problems regarding magnetic

amplifiers. The function generator was difficult to construct and keep operating, however, and discontinuities in the output of the generator gave rise to numerous problems in the simulation. The problems created by discontinuities in the output of this B-H function generator are of particular interest because they point out the advantages of a function generator that converts H into dB/dT. In the simulation of a circuit involving magnetic core devices, dB/dT will be a needed variable. If it is provided directly by a function generator, a subsequent computer differentiation is avoided.

### Simulation of A Saturable Transformer Circuit

An earlier report on this effort discussed several simulations of magnetic-core circuits, but no actual simulation results were included in the report (4). The most realistic of these simulations was modified slightly and gave excellent results in a simulation of a saturable transformer circuit.

Consider the saturable transformer circuit of Figure 7. The following equations describe this circuit.

$$1. \quad \mathcal{E}_a = i_1 R_1 + N_1 \left( d\phi/dt \right)$$

$$2. \quad \mathcal{E}_L = N_2 d\phi/dt = i_L R_L$$

$$3. \quad N_1 i_1 - N_2 i_L = \text{MMF}$$

$$4. \quad \text{MMF and } \phi \text{ are related as shown in Figure 8.}$$

It should be noted that the simulation described here is applicable for any number of secondary windings on the saturable transformer core.

Referring to the computer program of Figure 9, the following observations should be made. It is typical of analog computer programs in that it appears to be a "boot strap" operation. In amplifier 21, the terms are summed that provide the absolute value of the voltage available to be integrated by the core. A voltage proportional to the MMF determines the proper sign of  $\mathcal{E}_1$ , so that the output of amplifier 23,  $\mathcal{E}_1'$ , differs from  $d\phi/dt$  only in that no provisions are made for the core to saturate. Integrating  $\mathcal{E}_1'$ , the output of integrator 16 becomes  $\phi$  which is limited at  $\pm \phi_s$ . Differentiating  $\phi$ , a realistic  $d\phi/dt$  is available at the output of amplifier 5.

With  $d/dt$  and the applied voltage,  $e_a$ , available, the remaining variables are readily obtained, including the terms needed to compute  $e_1$ .

Consider the operation of the simulation for a sinusoidal input. If  $e_a$  is zero at time equal zero, the sum of the inputs to amplifier 21 remains positive until the absolute value of  $e_a$  exceeds plus  $\text{Imag } R_1$ , where  $\text{Imag}$  is the magnetizing current corresponding to  $(\text{MMF})_c$  in Figure 8. Amplifier 21 inverts the sum of the inputs and restricts the sum to positive values only. Once the absolute value of  $e_a$  exceeds  $\text{Imag } R_1$ ,  $e_1$  becomes a positive value, the proper sign is then inserted by amplifiers 17 and 23, and the resulting  $e_1$  is integrated to become  $\phi$ . Observe that the magnitude of  $e_a$  available to be integrated,  $e_1$ , is further reduced by the voltage drop in  $R_1$  due to load currents. Any number of secondary loads can be accounted for similarly.

Figures 10 through 16 illustrate the operation of this simulation for a 60 cycle sinusoidal input. The problem has been time scaled by a factor of  $10^{-3}$  and, consequently, operates at 0.060 cycles per second machine time. The figures are discussed in the following paragraphs. In every case, the value of  $\phi(B)$  is initially zero. Any permissible value of  $\phi$  can be inserted as an initial condition. The final value of  $\phi$  can also be readily determined by returning the computer to a "Hold" condition from "Operate" and reading the value of  $\phi$  on integrator 16.

#### Figure 10:

Figure 10 illustrates a no-load or open circuited secondary condition. The core is driven into saturation. A transient condition can be observed during the first half cycle.

#### Figures 11 and 12:

These figures illustrate a loaded secondary condition. Figure 12 is identical to Figure 11 except that secondary current rather than primary current is a variable in Figure 12. As before, the core is driven to saturation and a transient condition is noted during the first half cycle.

#### Figures 13 and 14:

Figures 13 and 14 correspond to Figures 11 and 12, respectively, with the secondary load doubled.

#### Figures 15 and 16:

In Figures 15 and 16, the excitation has been reduced to less than critical. The loads and variables plotted are the same as in Figures 13 and 14, respectively.

Although the computer runs recorded here were made for a sinusoidal excitation, the operation of this circuit should be satisfactory for any excitation. It is also expected that any number of linear or non-linear loads could be included in this

simulation. In the simulation discussed here, any circuit parameter can be readily changed. The core loop width is controlled by a pot setting and the saturating flux can be adjusted by fixing the limits on integrator 16. Both of these values can be made variables in more complex simulations. One significant disadvantage is the necessity of differentiating the output of integrator 16 to obtain  $d\Phi/dT$ . Differentiation is always avoided whenever possible in an analog computer.

Table I lists all the potentiometer settings for this circuit simulation, and the core parameters can be read from the computer charts.

### Conclusions and Extensions

The simulation of a saturable transformer circuit discussed here illustrates a technique by which the idealized characteristics of a square-loop core can be included in a circuit simulation. The simulation of the square-loop core is artificial in that the characteristics of the core are fixed and any changes in an actual core due to stresses will not appear in the simulation. The width of the square loop can be made proportional to one or more variables by including one or more multipliers in a more complex simulation, and the saturation flux,  $\Phi_s$  can be varied by making the limits on integrator 16 in figure 9 a variable. These measures could improve the simulation, but by no means perfect it.

The magnetic core characteristics included in the simulation are good approximations, however, and the circuit simulation is accurate and useful. There is no apparent reason why more complex circuits could not be simulated with the square-loop core simulation illustrated here.

A logical extension to this effort would be to simulate circuits using switching transistors. Transistors with low values of saturating base currents can likely be inserted directly into the simulation by computing the base-emitter voltage and applying it directly to the transistor. It is necessary that the computer amplifiers be capable of saturating the transistor.

A major incentive for this effort was the thought that a simulation of a circuit would provide a model into which faults could be inserted and the results observed. Conventional and new techniques will undoubtedly be applied to such studies, but several considerations are generally pertinent to analog computers and should be pointed out. Every variable in a computer simulation has been amplitude scaled so that the variable fits the operating range of the computer. If a short circuit is to be inserted such that a current will increase to 100 times its normal value, for example, that current will probably have to be rescaled to provide

for the increased amplitude. In many cases, large portions of a simulation will require rescaling to provide for the fault conditions. Also, the simulation should provide for the fact that any current path has some impedance when inserting a shorted condition.

In some instances, faults will be more difficult to simulate. An amplifier, for example, may be represented by a constant gain under normal conditions. If it is over-loaded by a fault condition, however, a simulation of the amplifier alone could become very complex if the fault condition is to be observed.



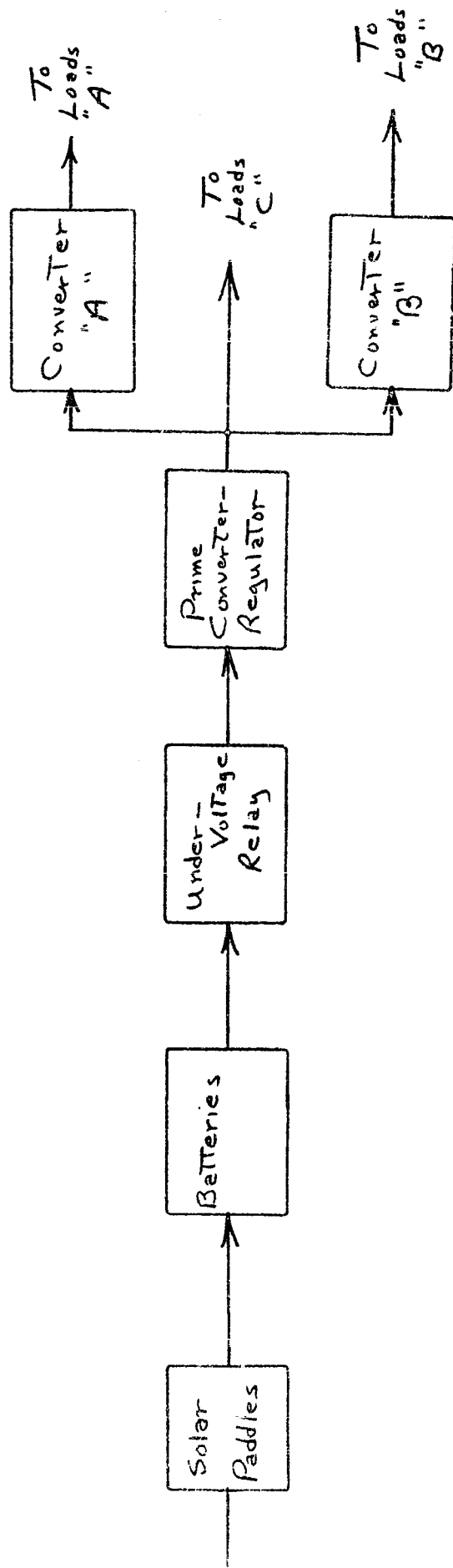
References

1. EVALUATION OF FERROMAGNETIC MATERIALS IN TERMS OF THE HARMONIC CONTENT OF ASSOCIATED MAGNETIC FIELDS, J. L. Artley.  
Dissertation, The John Hopkins University, Baltimore, Md. , 1956.
2. HARMONIC ANALYSIS FOR NONLINEAR CHARACTERISTICS, L. J. Lewis.  
AIEE TRANSACTIONS, pt. 1, v. 73, Jan. 1955.
3. FERROMAGNETIC DOMAIN THEORY, C. Kittel, J. K. Galt. Solid State Physics, Vol. 3, Book, Academic Press Inc., New York, N. Y., 1956, pp 534 - 51.
4. RESEARCH ON SATELLITE ELECTRICAL POWER CONVERSION SYSTEMS AND CIRCUIT PROTECTION, T. G. Wilson. Second Semiannual Status Report, Research Grant No. NSG - 152-61, Duke University, Durham, N. C., June, 1962.
5. ANALOG SIMULATION OF MAGNETIC AMPLIFIER CIRCUIT, H. Takehashi.  
Thesis, Waseda University, Tokyo, Japan, March 1961.
6. MAGNETIC HYSTERESIS FUNCTION GENERATOR, Sadamu Ohteru.  
AIEE CONFERENCE PAPER, Paper No. CP 62 - 124. May 31, 1961.
7. ON EXPRESSIONS OF MAGNETIC HYSTERESIS CHARACTERISTICS, S. Ohteru.  
AIEE TRANSACTIONS, Pt. III B, V. 78, 1959.

Table I

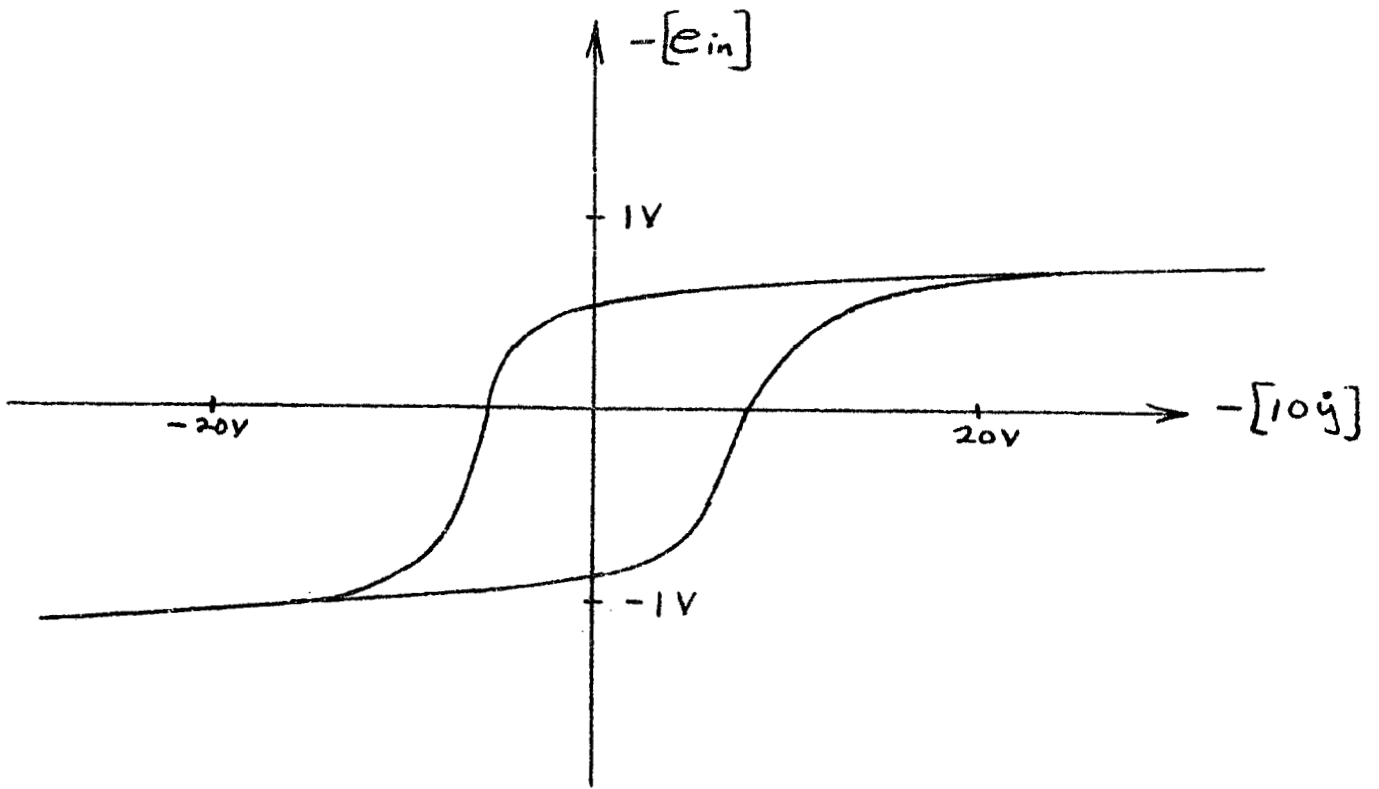
Computer Potentiometer Settings

<u>Pot. No.</u>	<u>Parameter Value</u>	<u>Setting</u>
3	-----	0.960
8	$\omega$	0.377
11	-----	1.000
13	$10^4/R_1$	1.000
15	$10^{-4} N_1 R_1/N_2$	0.960
16	-----	1.000
23	$0.5 \times 10^6/N_1$	0.270
25	$10^{-4} R_1 N_2/N_1$	0.850
27	$\omega$	0.377
44	$10^{-2} I_{mag} R_1$	0.070
45	$C_a(\text{Maximum Value})$	-----
46	$5 N_2/R_L$	-----
47	$10^{-3} N_1$	0.920



Simplified Satellite Electrical Power System

Figure 1



Example of a Hysteresis Loop Generated Analytically Using the Van der Pol Equation

Figure 2

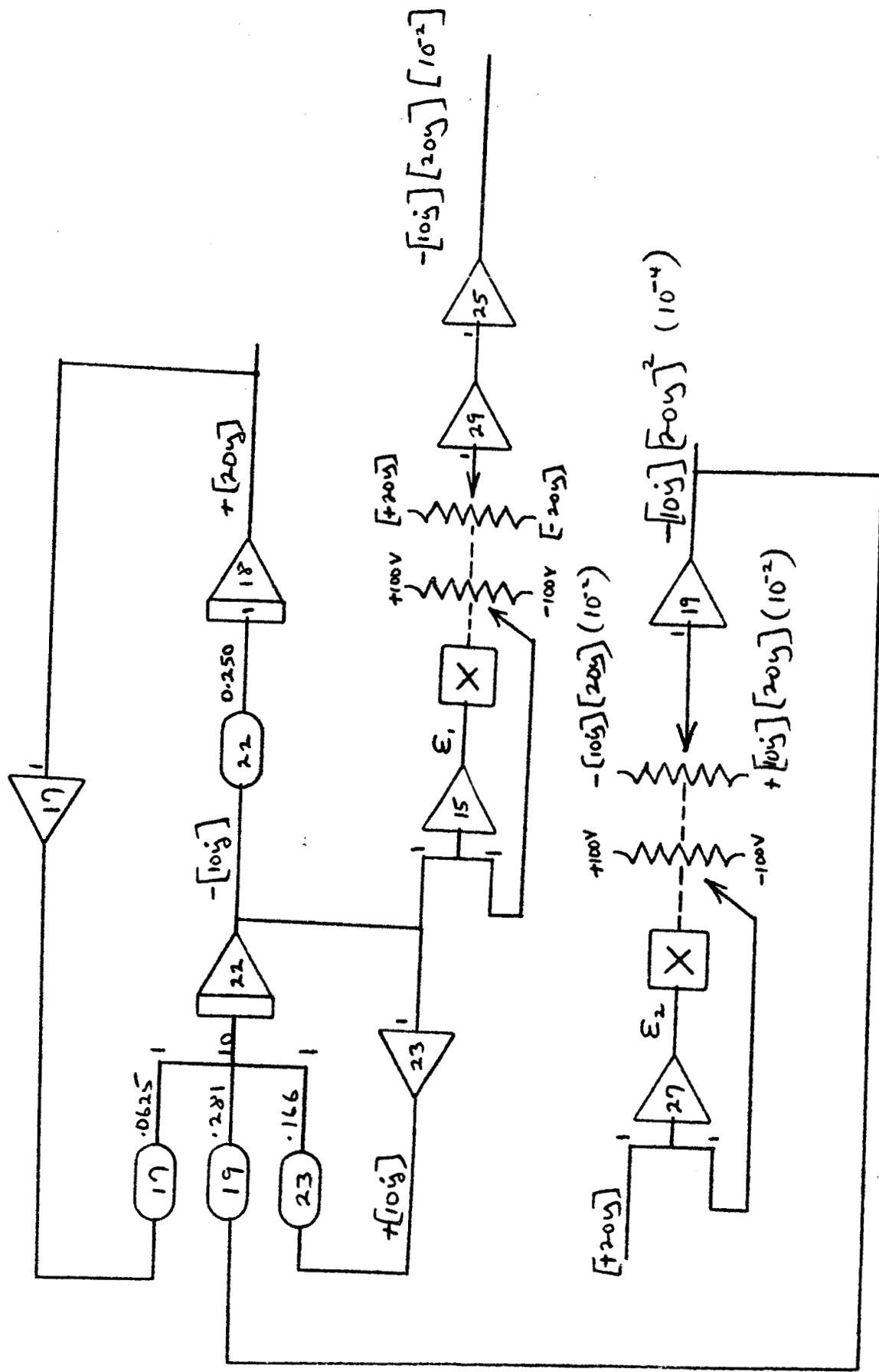


Figure 3 Simulation of Vander Pol's Equation

$$\ddot{y} = 0.9(1 - y^2)\dot{y} - y \quad \text{Time Scale} = 1/8$$

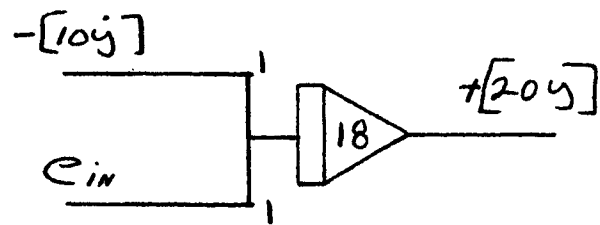


Figure 4

Illustration of H Input To Van der Pol  
B-H Function Generator

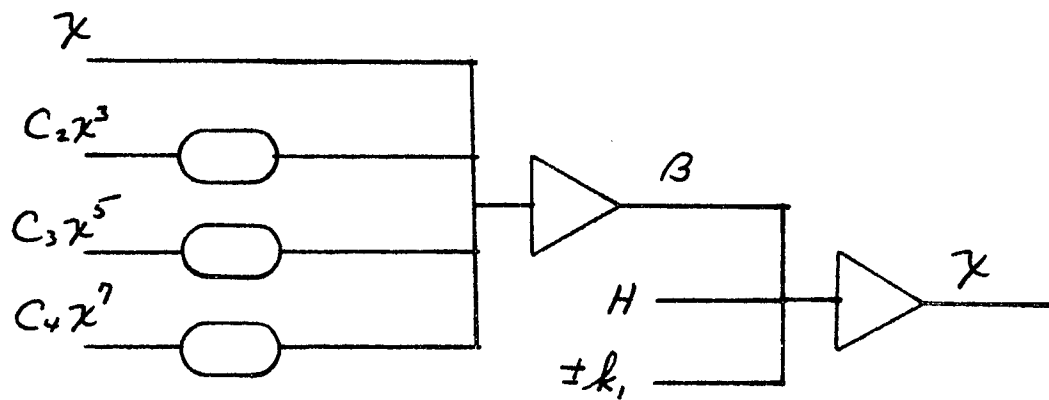
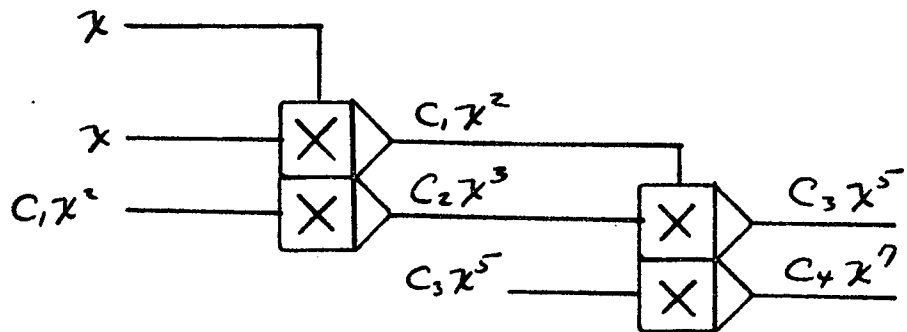


Figure 6

Analog Computer Solution To  
 $B = \tanh (B + H \pm k_1)$

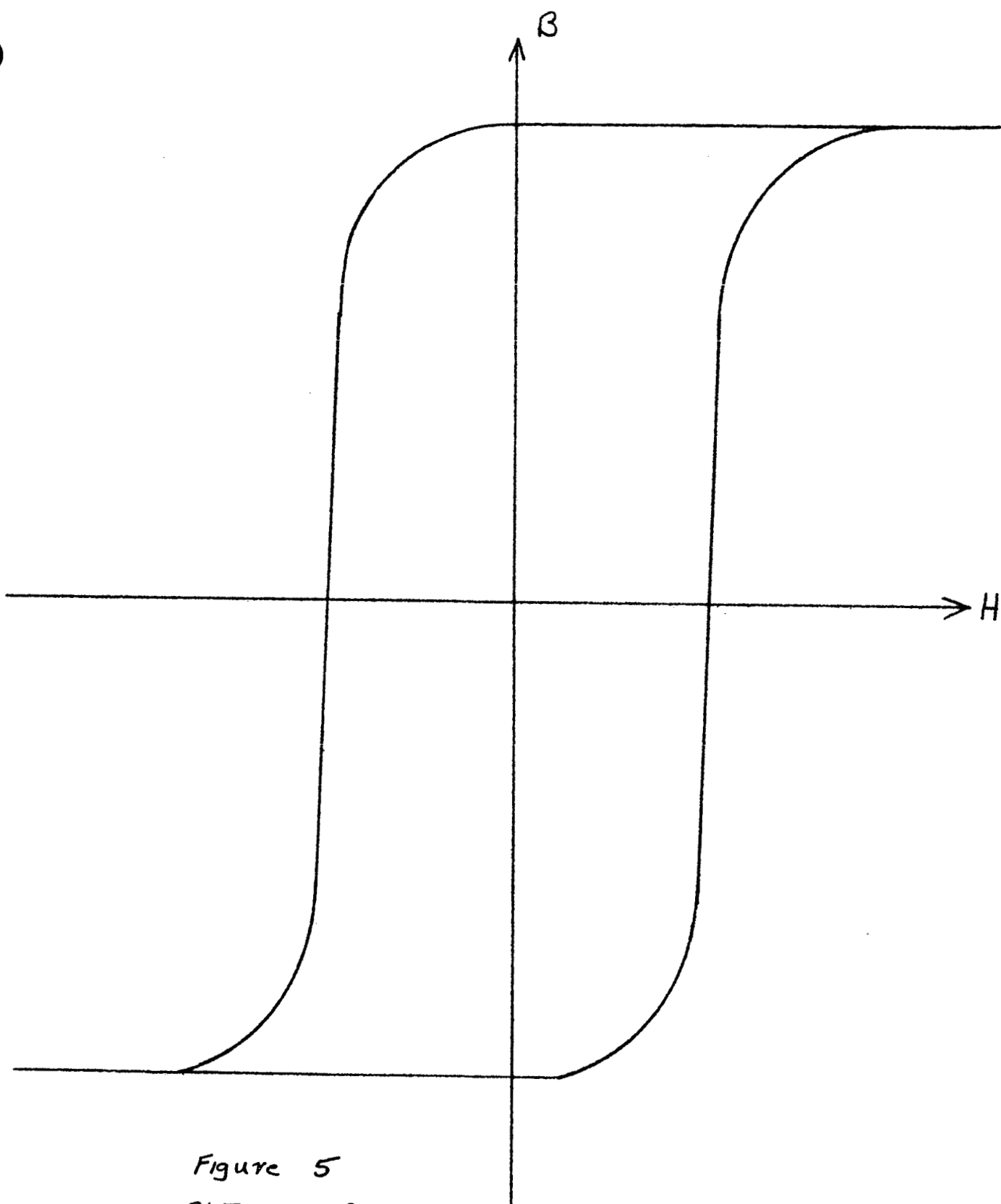


Figure 5  
Plot of  $\beta = \tanh(\beta + H \pm 2)$

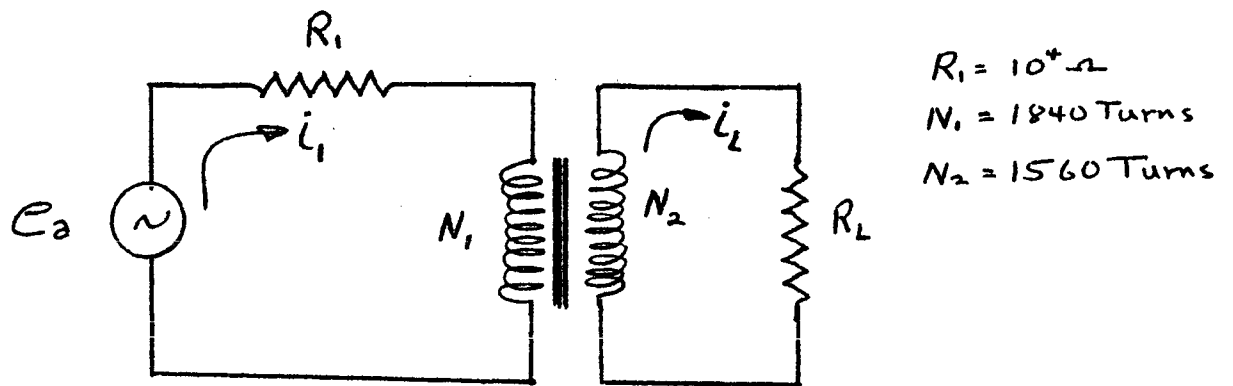


Figure 7 Saturable Transformer Circuit

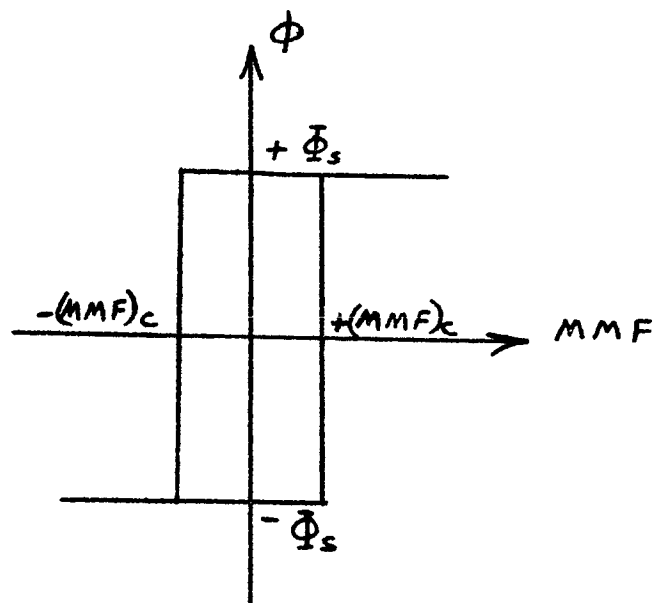


Figure 8 Characteristics of the Saturable Core



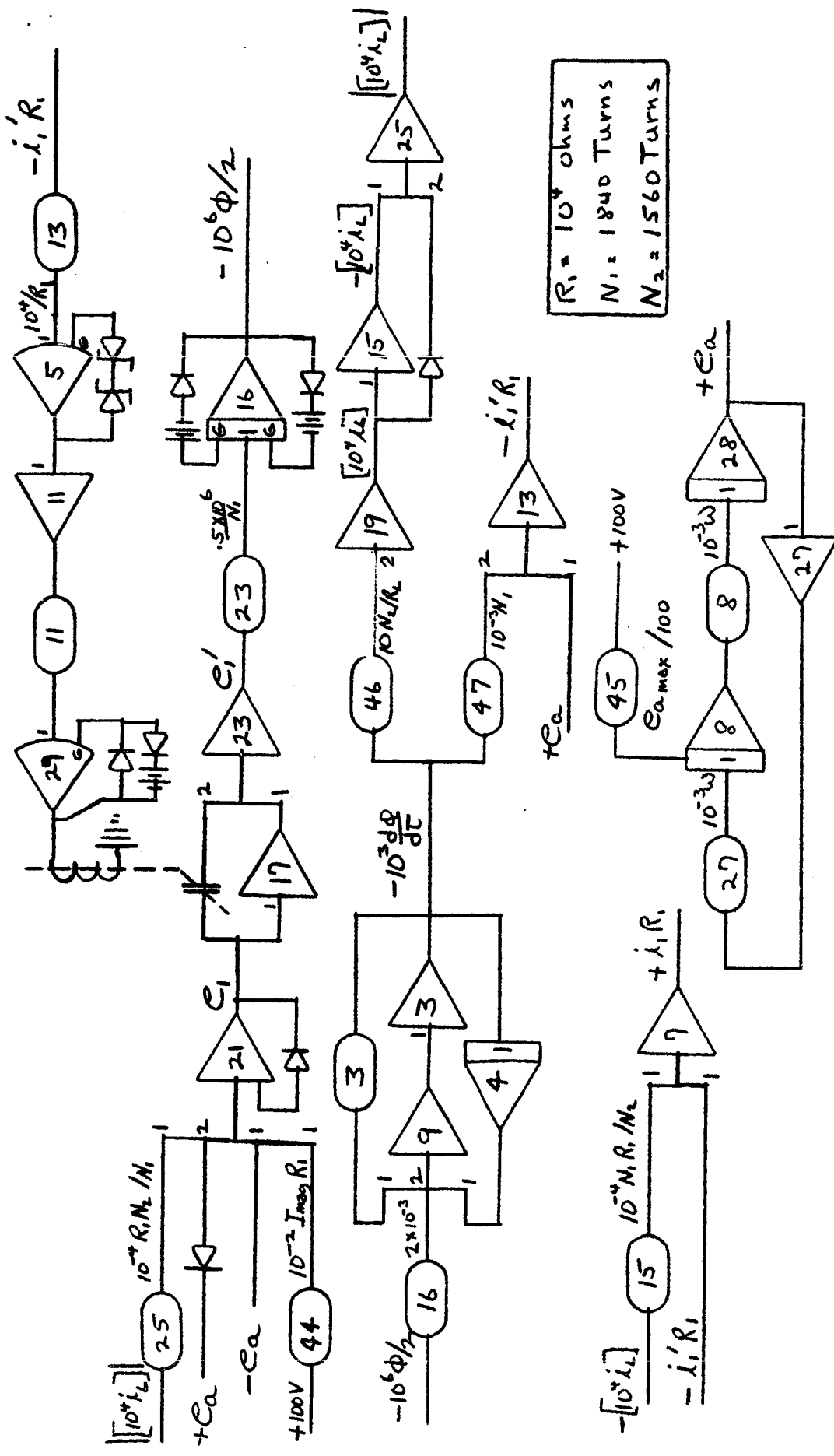


Figure 9 Analog Simulation of a Saturable Transformer Circuit

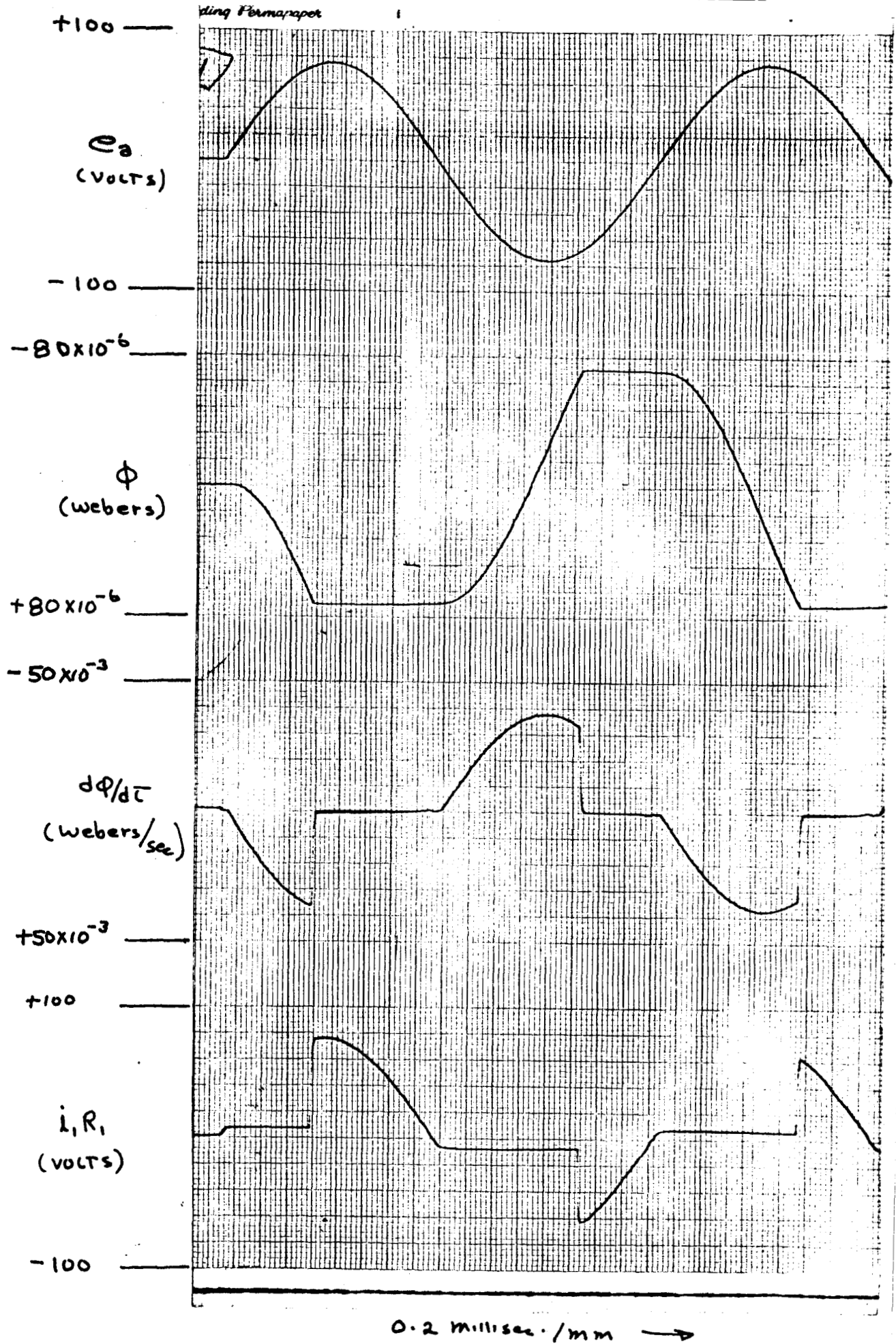


Figure 10 - No Load Condition

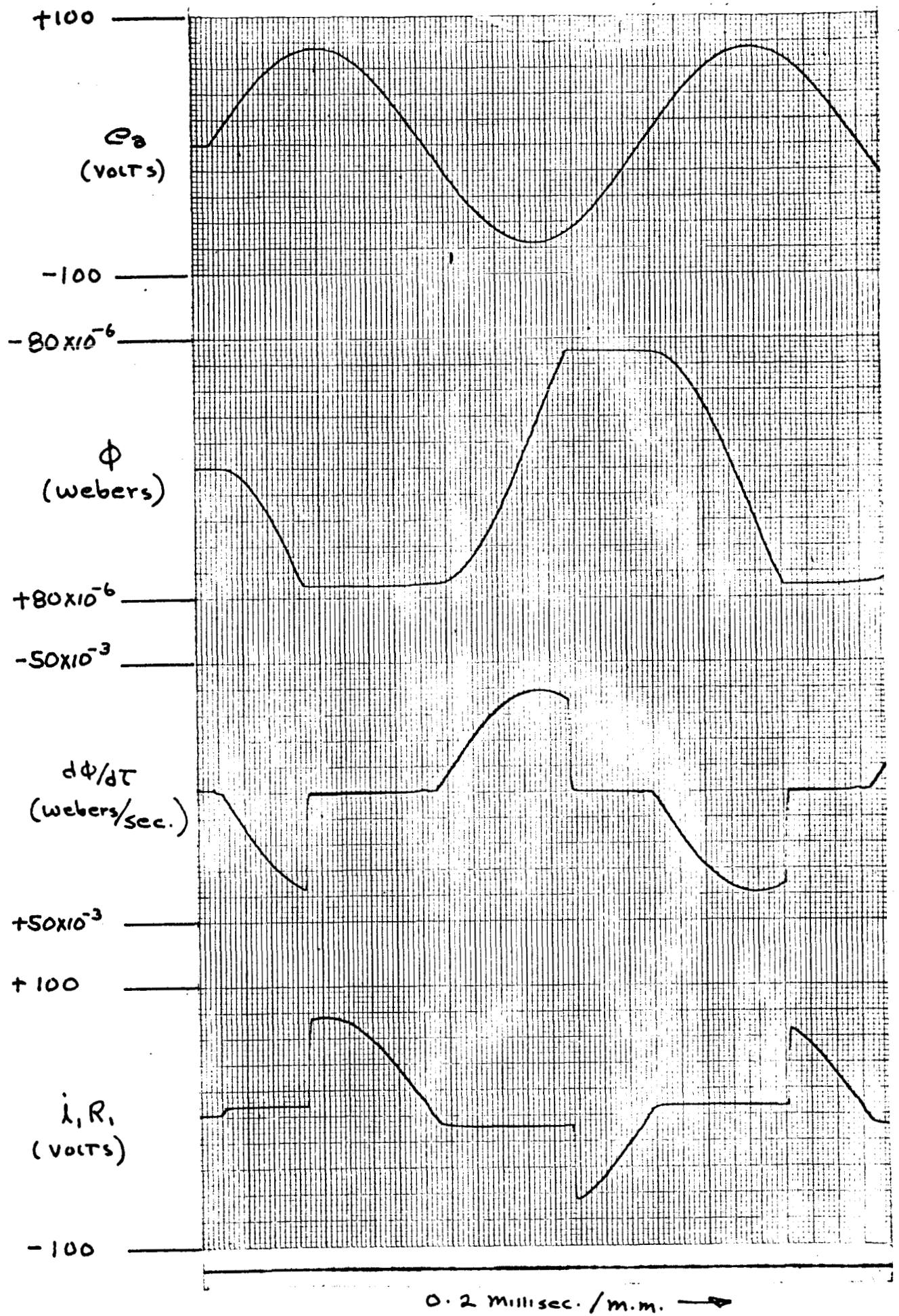


Figure 11  $R_L = 15.6 \text{ k}\Omega$

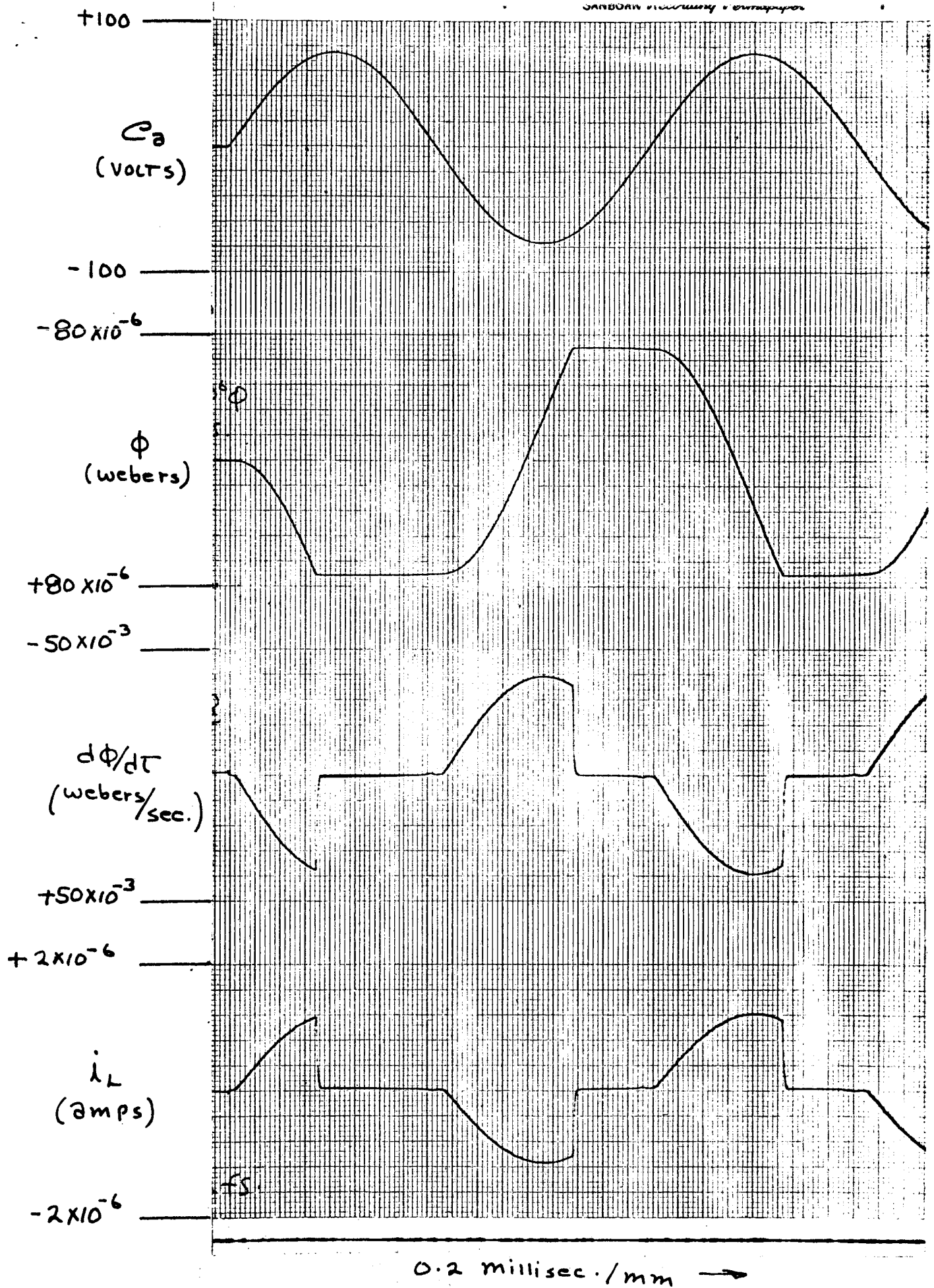


Figure 12

$$R_L = 15.6 \text{ K } \Omega$$

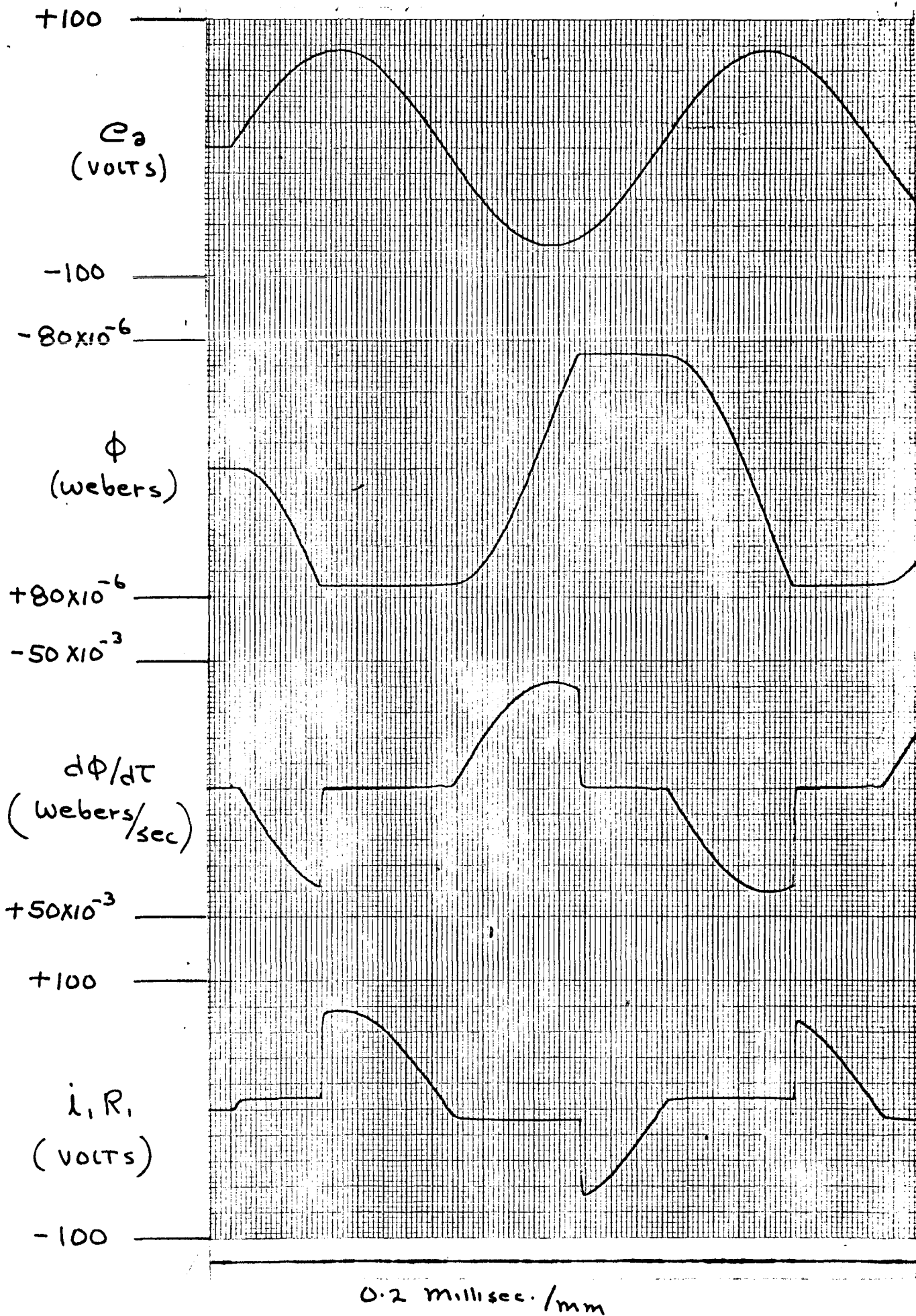


Figure 13

$$R_L = 7.8 \text{ k}\Omega$$



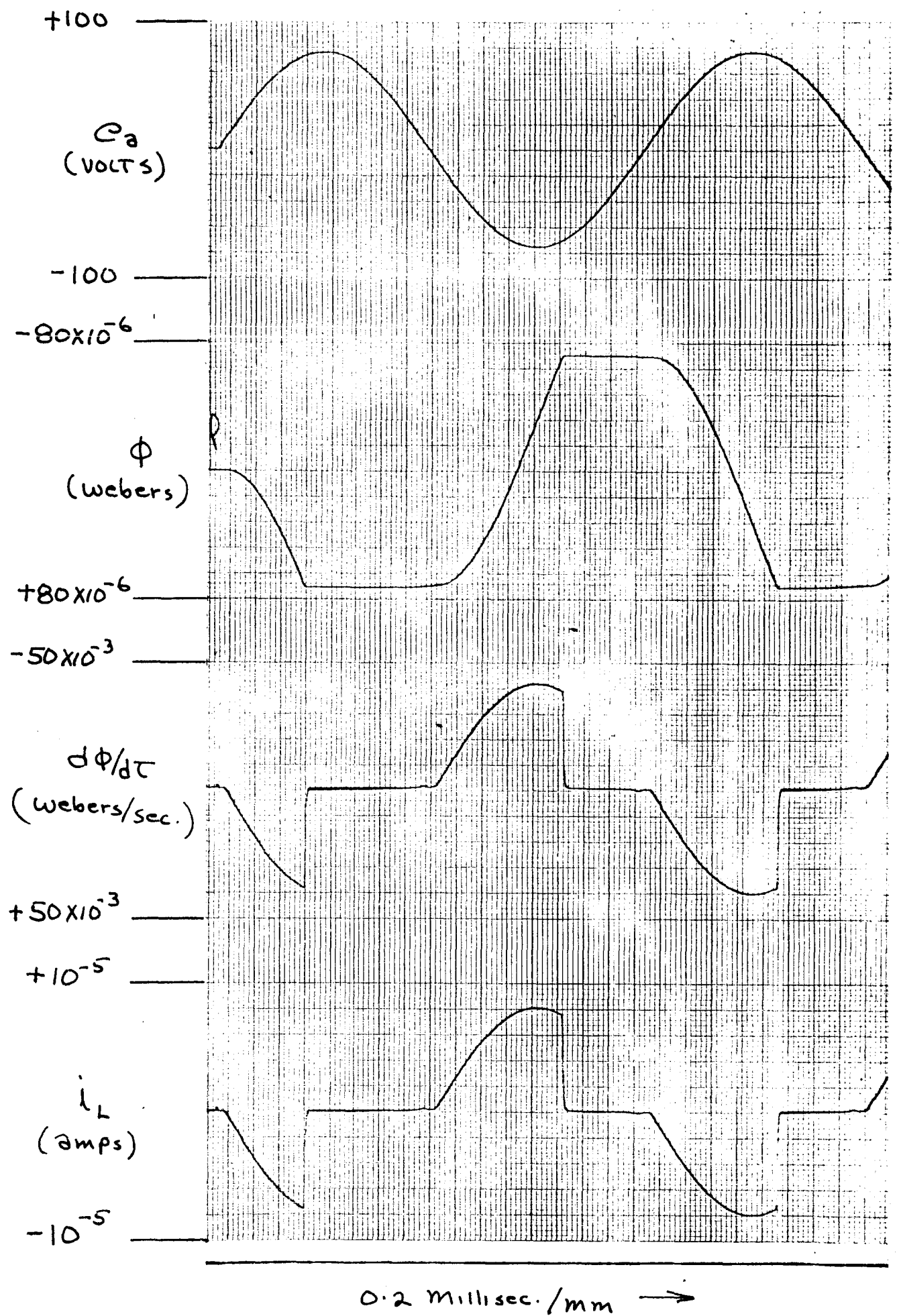


Figure 14

$$R_L = 7.8 \text{ K}\Omega$$

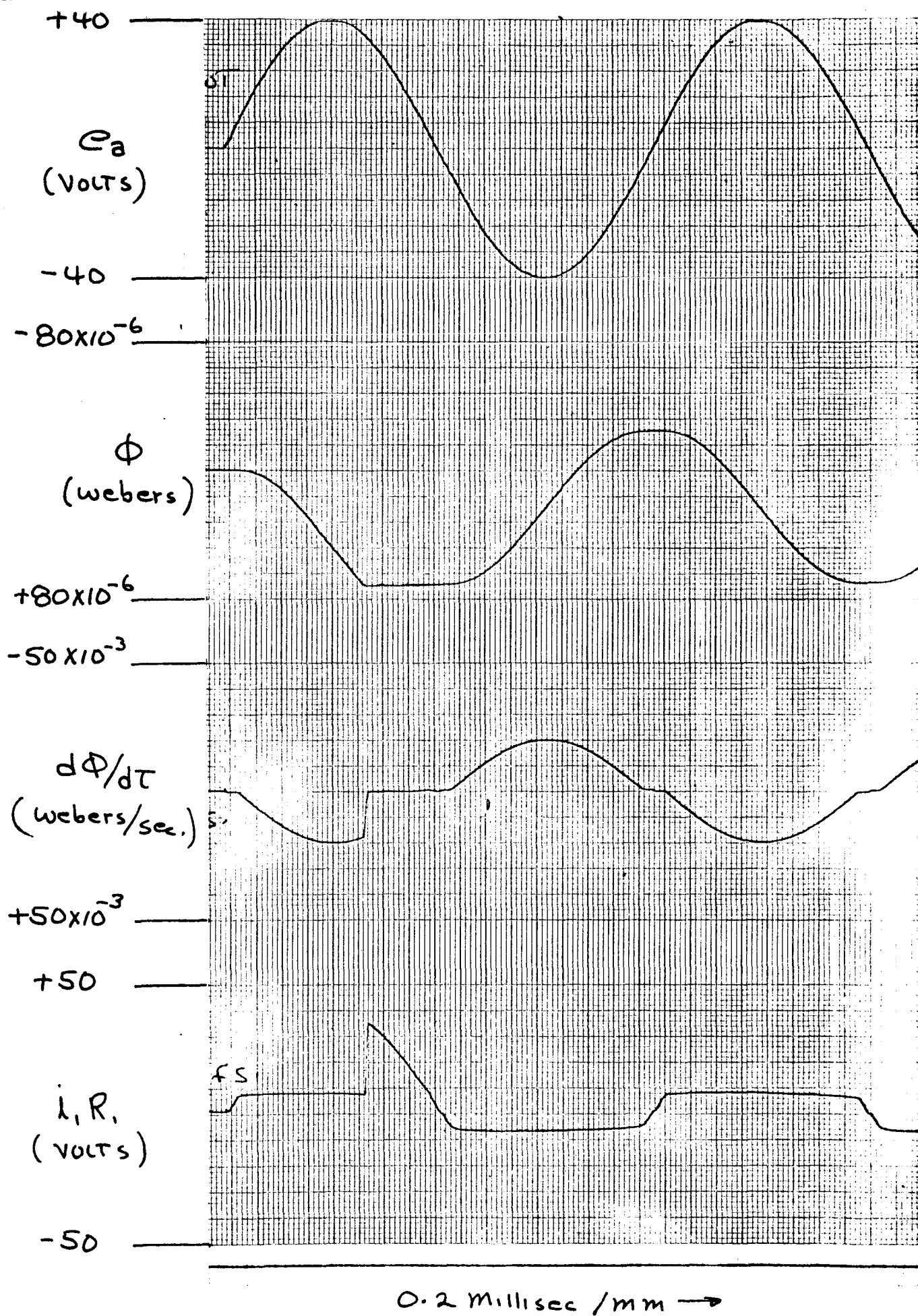


Figure 15

$$R_L = 7.8 \text{ k}\Omega$$

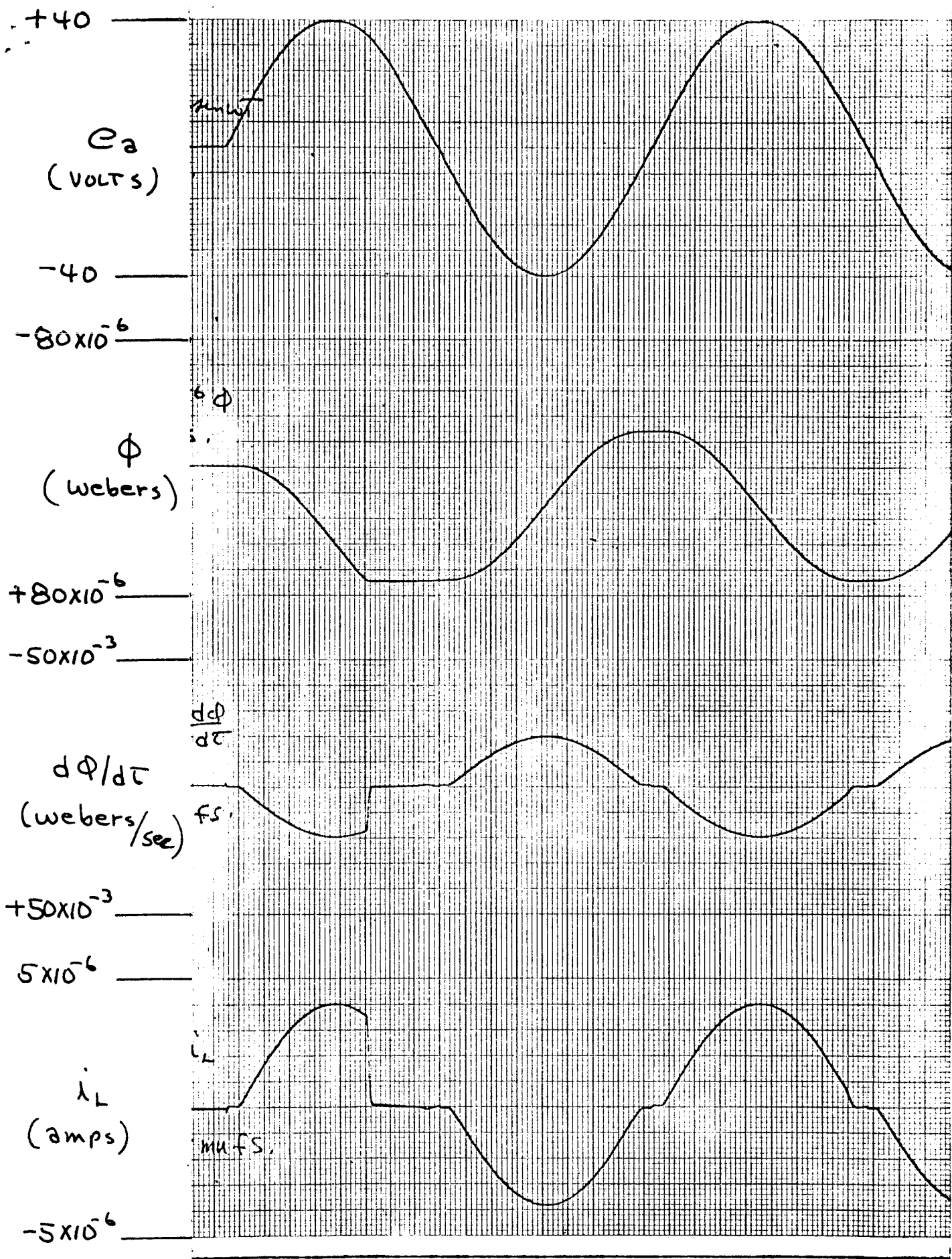


Figure 16

$$R_L = 7.8 \text{ K}\Omega$$